

AFOSR-TR- 88 - 0753

AD-A198 247

DTIC FILE COPY

UDR-TR-88-75

LASER MEASUREMENTS OF TRANSIENT HIGH-STRENGTH ELECTRIC FIELD:

R. J. Becker  
University of Dayton  
Research Institute  
Dayton, Ohio 45469

July 15, 1988

FINAL REPORT FOR PERIOD 1 OCTOBER 1985 TO 30 DECEMBER 1987

DISTRIBUTION UNLIMITED

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH  
BOLLING AIR FORCE BASE  
WASHINGTON, DC 20332-6448

DTIC  
ELECTE  
AUG 12 1988  
S D  
E

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

## REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION <b>Unclassified</b>			1b. RESTRICTIVE MARKINGS										
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT <b>Distribution unlimited</b>										
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE													
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING INSTRUMENT REPORT NUMBER(S) <b>AFOSR TR: 88-0753</b>										
6a. NAME OF PERFORMING ORGANIZATION <b>University of Dayton Research Institute</b>		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION <b>Air Force Office of Scientific Research (AFOSR/NA)</b>										
6c. ADDRESS (City, State and ZIP Code) <b>300 College Park Dayton, Ohio 45469-0001</b>		7b. ADDRESS (City, State and ZIP Code) <b>Bolling Air Force Base Washington, D.C. 20332-6448</b>											
8a. NAME OF FUNDING/SPONSORING ORGANIZATION <b>Office of Scientific Research</b>		8b. OFFICE SYMBOL (If applicable) <b>AFOSR/NA</b>	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER <b>AFOSR-84-0232</b>										
8c. ADDRESS (City, State and ZIP Code) <b>Bolling Air Force Base Washington, D. S. 20332-6448</b>		10. SOURCE OF FUNDING NOS. <table border="1"><tr><th>PROGRAM ELEMENT NO.</th><th>PROJECT NO.</th><th>TASK NO.</th><th>WORK UNIT NO.</th></tr><tr><td><b>011102+</b></td><td><b>2308</b></td><td><b>A1</b></td><td></td></tr></table>				PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.	<b>011102+</b>	<b>2308</b>	<b>A1</b>	
PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.										
<b>011102+</b>	<b>2308</b>	<b>A1</b>											
11. TITLE (Include Security Classification) <b>Laser Measurement of Transient (see reverse)</b>													
12. PERSONAL AUTHOR(S) <b>Roger J. Becker</b>													
13a. TYPE OF REPORT <b>Final</b>		13b. TIME COVERED <b>FROM 10/1/85 TO 12/30/87</b>		14. DATE OF REPORT (Yr., Mo., Day) <b>7/15/87</b>									
15. PAGE COUNT													
16. SUPPLEMENTARY NOTATION													
17. COSATI CODES <table border="1"><tr><th>FIELD</th><th>GROUP</th><th>SUB. GR.</th></tr><tr><td><b>20</b></td><td><b>06</b></td><td></td></tr></table>			FIELD	GROUP	SUB. GR.	<b>20</b>	<b>06</b>		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) <b>Rayleigh scattering Electric field measurement Nonlinear optics</b>				
FIELD	GROUP	SUB. GR.											
<b>20</b>	<b>06</b>												
19. ABSTRACT (Continue on reverse if necessary and identify by block number) <p>An experiment was undertaken to determine the usefulness of Rayleigh and Raman scattering as a nonintrusive probe for measuring local electric field strengths. Measurements were made using an argon-ion laser, photon counting electronics, and a 30 kV Stark cell capable of pressurization to 1 MPa. This system was successfully used with He, Ne, Ar, Kr, N<sub>2</sub>, CO<sub>2</sub>, CF<sub>4</sub>, CH<sub>4</sub>, SF<sub>6</sub>, and CCl<sub>2</sub>F<sub>2</sub> gases using a right-angle scattering configuration in which the observation direction was along the axis of polarization of the laser beam. In all cases, a drop was seen in the counting rate for Rayleigh scattering.</p> <p>A means of calculating the observed effect in Rayleigh scattering was selected based on quantum perturbation theory. This method used both a Coulomb approximation and a single-electron approximation. A computer code was written to implement the perturbation</p> <p>(see reverse side)</p>													
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <b>UNCLASSIFIED/UNLIMITED</b> <input checked="" type="checkbox"/> SAME AS RPT <input checked="" type="checkbox"/> DTIC USERS <input checked="" type="checkbox"/>			21. ABSTRACT SECURITY CLASSIFICATION <b>Unclassified</b>										
22a. NAME OF RESPONSIBLE INDIVIDUAL <b>Mithat Birkan</b>		22b. TELEPHONE NUMBER (Include Area Code) <b>(202) 767-4938</b>		22c. OFFICE SYMBOL <b>AFOSR/NA</b>									

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

Block 11 (Continued)

High-Strength Electric Fields

Block 19 (Continued)

scheme. This code requires input in the form of matrix elements taken from tables in the literature. As not all of the needed entries are available in published form, a second program was being written to extend the published tables. The computer calculations were made to give all contributions to the polarizability including those involving more than one continuum state.

Raman spectra were unchanged by 10 MV/m applied fields. Raman measurements were made in  $\text{CO}_2$ ,  $\text{N}_2$ ,  $\text{CCL}_2\text{F}_2$ ,  $\text{SF}_6$ ,  $\text{NH}_4$ , and liquid benzene. Fourth-rank tensors were found for the  $\text{D}_{6h}$ ,  $\text{C}_{3v}$ ,  $\text{O}_h$ ,  $\text{C}_{2v}$ , and  $\text{D}_{\infty h}$  point groups.

Unclassified

UDR-TR-88-75

LASER MEASUREMENTS OF TRANSIENT HIGH-STRENGTH ELECTRIC FIELDS

R. J. Becker  
University of Dayton  
Research Institute  
Dayton, Ohio 45469

July 15, 1988

FINAL REPORT FOR PERIOD 1 OCTOBER 1985 TO 30 DECEMBER 1987

DISTRIBUTION UNLIMITED

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH  
BOLLING AIR FORCE BASE  
WASHINGTON, DC 20332-6448

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

QUALITY  
INSPECTED  
2

## TABLE OF CONTENTS

<u>SECTION</u>		<u>PAGE</u>
1	OBJECTIVES	1
2	STATUS	2
3	TECHNICAL JOURNALS	23
4	PROFESSIONAL PERSONNEL	24
5	INTERACTIONS	25
6	PATENTS	29
7	ADDITIONAL CONSIDERATIONS	30

## LIST OF ILLUSTRATIONS

<u>FIGURE</u>		<u>PAGE</u>
1	Change in Signal for Rayleigh Scattering from Freon-14 Due to the Application of a 6 MV/m Electric Field.	4
2	Plot of Oscillator Strength Distribution in the Continuum for the Ground State of Helium.	11
3	Plot of Oscillator Strength Value at the Spectral Head for $np \rightarrow md$ Transitions vs. $n$ .	12
4	Plot of Oscillator Strength Value at the Spectral Head $np \rightarrow ms$ Transitions vs. $n$ .	13
5	Plot of Oscillator Strength Value at the Spectral Head for $ns \rightarrow mp$ Transitions vs. $n$ .	14
6	Plot of Oscillator Strength Distribution in the Continuum for the $2p \rightarrow$ Continuum, $\ell=2$ vs. Energy of the Continuum State.	15

# LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
1	Normalized Cross Section for Forward Scattering.	5
2	Reduced Data for Forward Scattering	6
3	Reduced Data for Right-Angle Scattering.	7
4	Oscillator Strengths for Transition from $1^1s$ to $N^1P$ in Helium.	9
5	Oscillator Strengths for Transitions from $2^1P$ to $3^1D$ in Helium.	10
6	Contributions to the Sum of the Oscillator Strengths for $2^1P$ to $3^1P$ Helium States.	16
7	Contribution to the Polarizability Terms <sup>†</sup> .	17
8	Field-Induced Scattering Tensors for Raman Activity of the $C_s$ and $C_{2v}$ Point Groups.	19
9	Field-Induced Scattering Tensors for $D_{6h}$ and $D_{\infty h}$ Point Groups.	20
10	Field-Induced Scattering Tensors for the $O_h$ and $C_{3v}$ Point Groups.	21

## 1. OBJECTIVES

This program investigated the utility of a nonintrusive approach to a direct measurement of transient electric fields in plasmas of general interest. The motivation for the program was the fact that current knowledge of the transient behavior of non-equilibrium plasmas is limited. It is known that the behavior of a plasma is a sensitive function of the local electric field strength. Unfortunately, general-purpose methods for measuring transient electric fields in plasma environments with good spatial resolution have not yet been developed. In response to this need, the long-term goal of this research was to devise a nonintrusive method of measuring electric field strengths that (a) is suitable for a wide range of gases of importance, (b) is sensitive, and (c) requires no spectral scanning. The broad research goal was to perform Rayleigh and Raman scattering measurements and to calculate the Rayleigh polarization tensor for atoms and Raman polarization tensors for molecules as a function of applied electric field strength. In short, we anticipated performing quantum perturbation and group theoretical calculations and measurements of scientific value in atomic and molecular physics. It was argued that this work would enable us to measure electric fields in hostile environments with good spatial and temporal resolution. Such measurements are expected to aid in the development of high-performance power devices of various types and to advance the plasma physics of hard-driven and unstable plasmas.

Our specific objectives were to perform Rayleigh measurements in several gases, calculate the Rayleigh polarization tensor for these gases, perform quantum perturbation calculations, conduct experiments on the Stark effect on Raman scattering, and use group theory to predict Raman scattering possibilities.



## 2. STATUS

Rayleigh measurements were completed on a variety of atomic and nuclear gases, including both isotropic and nonisotropic gases. This work established that Rayleigh scattering is not a feasible electric-field diagnostic for gases or plasmas. The quantum perturbation calculations were completed for all transitions between discrete states, between discrete and continuum states, and between pairs of continuum states.

Raman scattering measurements were conducted on  $N_2$ ,  $CO_2$ ,  $CCL_2F_2$ ,  $NH_4$ , and  $SF_6$  at pressures up to 120 psi (840 kPa) and field strengths up to 120 kV/cm (12 MV/m). No electric field induced result was detected. Group theoretical calculations of the Stark-induced Raman scattering tensors were made for six-point groups. These calculations showed that Stark-induced changes in Raman spectra should exist in principle. Raman measurements were also made on liquid benzene at field strengths up to 80 kV/cm (8MV/m). Again, no changes in the recorded spectra were observed.

Rayleigh measurements were made on He, Ne, Ar, Kr,  $N_2$ , air,  $CO_2$ ,  $CF_4$ ,  $SF_6$ ,  $CH_4$ , and  $CCL_2F_2$  at pressures of 125 to 150 psi. This selection of gases enabled us to evaluate the pertinence of the degree of isotropy of the target species as well as the ionization potential of the gas. For safety reasons, toxic or flammable gases were not studied. In all cases, a small decrease in the signal, due to the presence of an applied dc electric field at a strength just below the breakdown potential of the gas, was observed. A number of investigations were made as a function of the scattering angle, the solid angle subtended by the collection optics, and the polarization vector of the incident light to determine the nature of the mechanism leading to the drop in signal. These studies suggest that the mechanism is a reduction in the ac polarizability of the gas due to the dc field.

However, the reduction in Tyndall scattering from submicron dust particles due to electrostatic precipitation remains a possibility. The difficulty in making an unambiguous identification of the observed effect was due to the poor signal-to-noise ratio for the experiment. Since the low signal level implies that Rayleigh scattering is not well suited for diagnostics on most plasmas of interest to the Air Force, and since our charter was to determine the feasibility of a technique, rather than pursue scientific research questions in depth, the Rayleigh measurements were terminated and work was initiated to set up Raman studies.

An example of the data from a series of Rayleigh scattering runs is shown in Figure 1. Field-induced cross sections are presented in Table 1. Reduced Rayleigh scattering data for forward and right-angle scattering are given respectively in Tables 2 and 3.

An in-depth theoretical investigation was made. Errors were found in the famous Bates and Damgaard paper containing tables that are used extensively in calculations of atomic interactions. These tables lacked the completeness and accuracy needed for third-order calculation, so we wrote a program to generate improved tables. Calculations of the polarizability and optical transitions between all important pairs of discrete states and between discrete states and the continuum were made. These are the transitions of greatest interest in emission, absorption, and fluorescence spectroscopy, as well as resonant Raman or CARS scattering. The quantum calculations were completed with a treatment of continuum-to-continuum transitions. No significant contribution to the Rayleigh cross section was found from the continuum-to-continuum transitions.

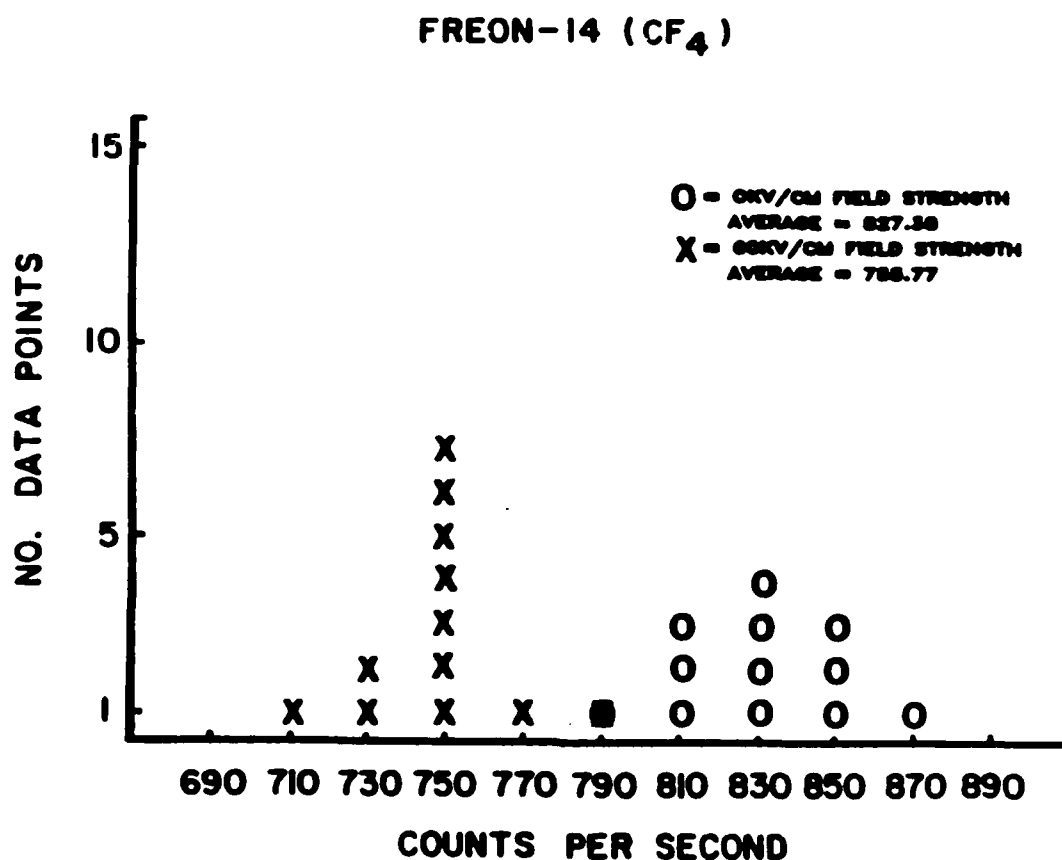


Figure 1. Change in Signal for Rayleigh Scattering from Freon-14 Due to the Application of a 6 MV/m Electric Field.

TABLE 1.  
NORMALIZED CROSS SECTIONS FOR FORWARD SCATTERING

GAS	Field-Induced Cross Section	Normalized SNR**
	$\frac{d\sigma_F^*}{d\Omega} \quad A$  (• 10 <sup>-30</sup> cm <sup>2</sup> /sr)	$\frac{\Delta\mu}{\sigma_{sA}} \quad F_p^{21/2}$  (• 10 <sup>-5</sup> $\frac{kV^2}{cm^4}$ kPa <sup>1/2</sup> )
Neon	4.2	800
CF <sub>4</sub>	.7	4
Nitrogen	.1	3
Air	3.5	9

\* Normalized to 10 kV/cm  
 \*\* Normalized to 10 kV/cm and STP

TABLE 2.  
REDUCED DATA FOR FORWARD SCATTERING

	Mean-Zero Field	Mean-Applied Field	Induced Field	Statistical Error	SNR
GAS (P)	$\mu_o^*$	$\mu_F^*$	F (kV/cm)	$\sigma_s^*$	$\frac{\Delta\mu}{\sigma_s}$
Neon (860 kPa)	3431	3343	5	15	6
Freon-14 (860 kPa)	154890	153480	60	320	5
Nitrogen (860 kPa)	49683	49558	60	43	3
Air (101 kPa)	5689	5627	60	20	3
* In counts/second					

TABLE 3.  
REDUCED DATA FOR RIGHT ANGLE SCATTERING

	Mean-Zero Field	Mean-Applied Field	Induced Field	Statistical Error	SNR
GAS (P)	$\mu_o^*$	$\mu_F^*$	F(kV/cm)	$\sigma_s^*$	$\frac{\Delta\mu}{\sigma_s}$
Helium (860 kPa)	180	175	15	1	6
Neon (860 kPa)	460	437	5	4	6
Argon (860 kPa)	6926	6760	42	19	9
Krypton (520 kPa)	9312	9213	27	16	6
Nitrogen (860 kPa)	9993	9965	60	3	8
Air (860 kPa)	9265	9222	60	13	3
10% CH <sub>4</sub> in argon (690 kPa)	6632	6561	40	20	4
SF <sub>6</sub> (760 kPa)	8378	8329	60	21	2
CF <sub>4</sub> (860 kPa)	29979	28652	60	154	9
CCl <sub>2</sub> F <sub>2</sub>					
* In counts/second					

The code used to make the theoretical predictions was checked against established calculations for oscillator strengths in Helium. Comparisons for several S-p and p-d transitions are given respectively in Tables 4 and 5. These tables show excellent agreement and vindicate our code. The code was then used to predict oscillator strengths for transitions that we were unable to find in the literature, especially transitions involving the continuum. These results are presented in Figures 2 - 6 and Table 6. A detailed description of both the experiment and the calculations is in preparation in a revision of a paper presented earlier to the Journal of Applied Physics. The oscillator strength values are of interest to researchers interested in atomic emission, absorption, and fluorescence. The predicted results for various contributions to the polarizability, which gives the Rayleigh scattering cross section, are given in Table 7. A small increase in the Rayleigh signal is predicted at the field strengths used in the experiment.

The high-pressure Raman experiments in gases were first made with a 1 m Jarrell-Ash monochromator and then repeated using an ISA U-1000 1 m double monochromator. Both the rotational and vibrational spectra were studied. Experiments were conducted to detect changes in the total scattering intensity from allowed lines, changes in polarization properties of these lines, and array-induced activities in lines which are normally Raman inactive. No changes were observed that could not be attributed to statistical fluctuations in the weak Raman signal or to emission from a Townsend current.

As Stark-induced Raman scattering has been observed in semiconductors at field strengths as low as 100 kV/cm (10 MV/m), a review was made of the theoretical possibility of observing an effect. Fourth-rank scattering tensors were calculated for the point groups  $D_{6h}$ ,  $C_{3v}$ ,  $O_h$ ,  $C_{2v}$ , and  $D_{\infty h}$ . These calculations showed that Stark-induced changes in the Raman spectra of

TABLE 4.  
OSCILLATOR STRENGTHS FOR  
TRANSITION FROM  $1^1S$  TO  $N^1P$   
IN HELIUM

	2P	3P	4P	5P
Variational	0.27616	0.07344	0.029863	0.015039
This Work	0.2665	0.07413	0.0306	0.0155
Percent Error	3.5	1.0	2.4	3.0



TABLE 5.  
OSCILLATOR STRENGTHS FOR  
TRANSITIONS FROM  $2^1P$  TO  $3^1D$   
IN HELIUM

	3 D	4 D	5 D	6 D	7 D	8 D	9 D
2'P	0.71016	0.12026	0.04326	0.02095	0.01190	0.007464	0.005015
	0.71103	0.12087	0.04357	0.02113	0.01201	0.007548	0.005062
3'P	0.02114	0.6481	0.1413	0.05629	0.02890	0.01708	0.01104
	0.02122	0.6484	0.1415	0.05637	0.02895	0.01712	0.01106
4'P	0.01531	0.0401	0.648	0.1529	0.0636	0.0336	0.02034
	0.01531	0.0402	0.648	0.1529	0.0636	0.0337	0.02036
5'P	0.00311	0.0393	0.0573	0.670	0.1632	0.0693	0.0373
	0.00311	0.0393	0.0576	0.670	0.1632	0.0693	0.0374

Upper value is from Reference 13. Lower value is from the present calculation.

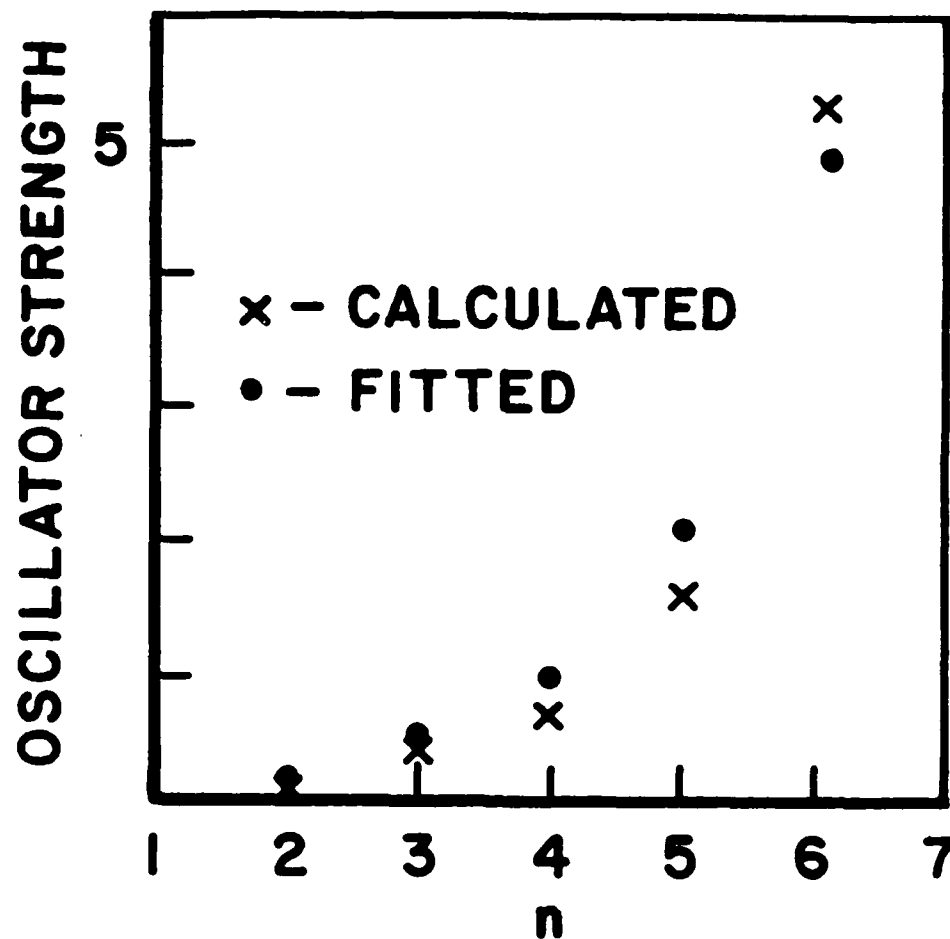


Figure 2. Plot of Oscillator Strength Distribution in the Continuum for the Ground State of Helium.

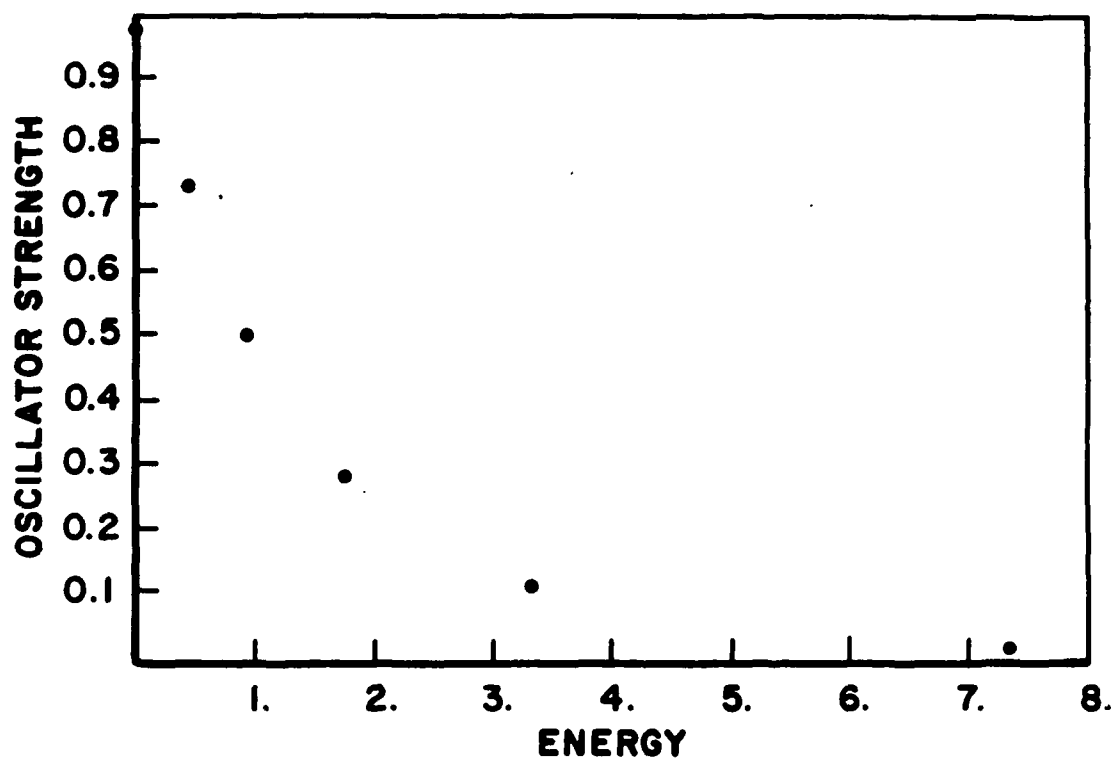


Figure 3. Plot of Oscillator Strength Value at the Spectral Head for  $np \rightarrow md$  transitions vs.  $n$ .

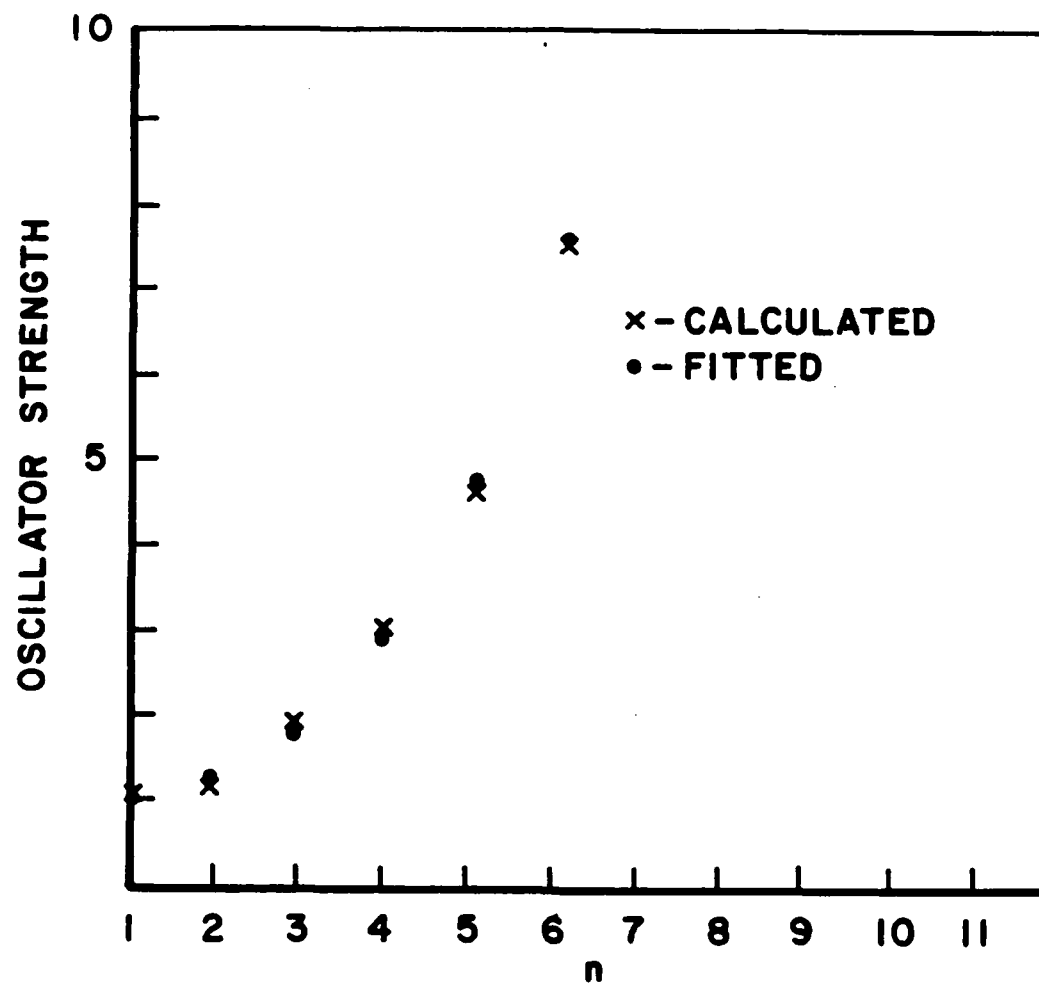


Figure 4. Plot of Oscillator Strength Value at the Spectral Head  $np \rightarrow ms$  Transitions vs.  $n$ .

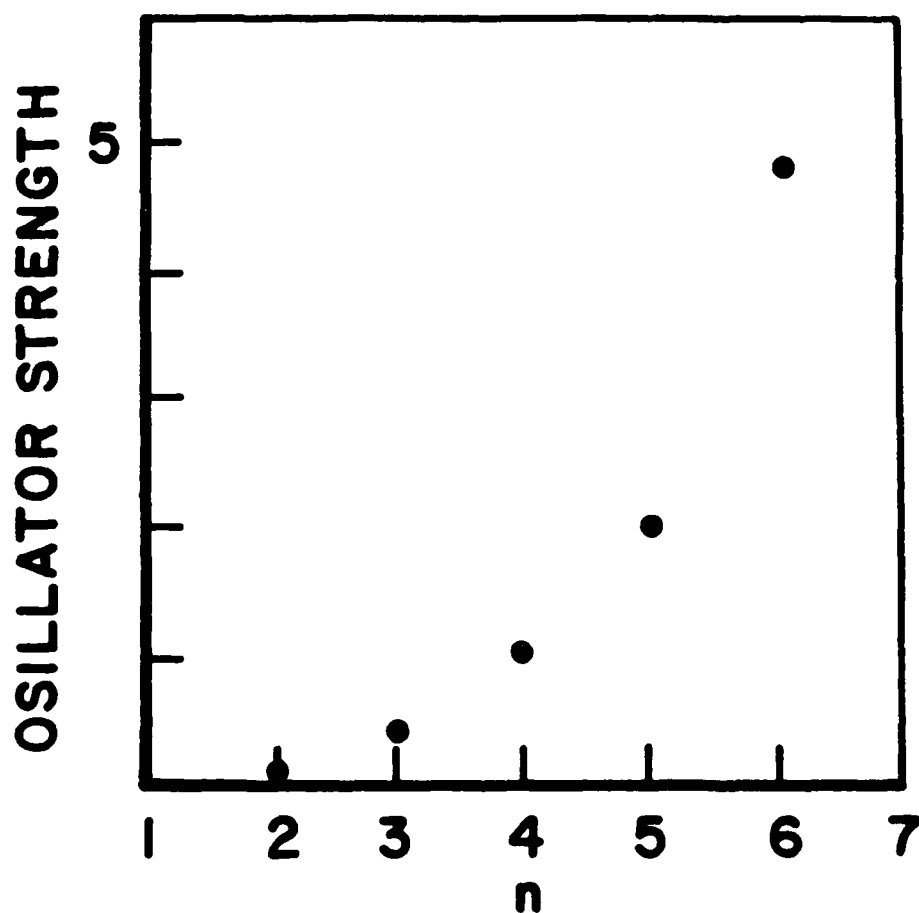


Figure 5. Plot of Oscillator Strength Value at the Spectral Head for  $ns \rightarrow mp$  Transitions vs.  $n$ .

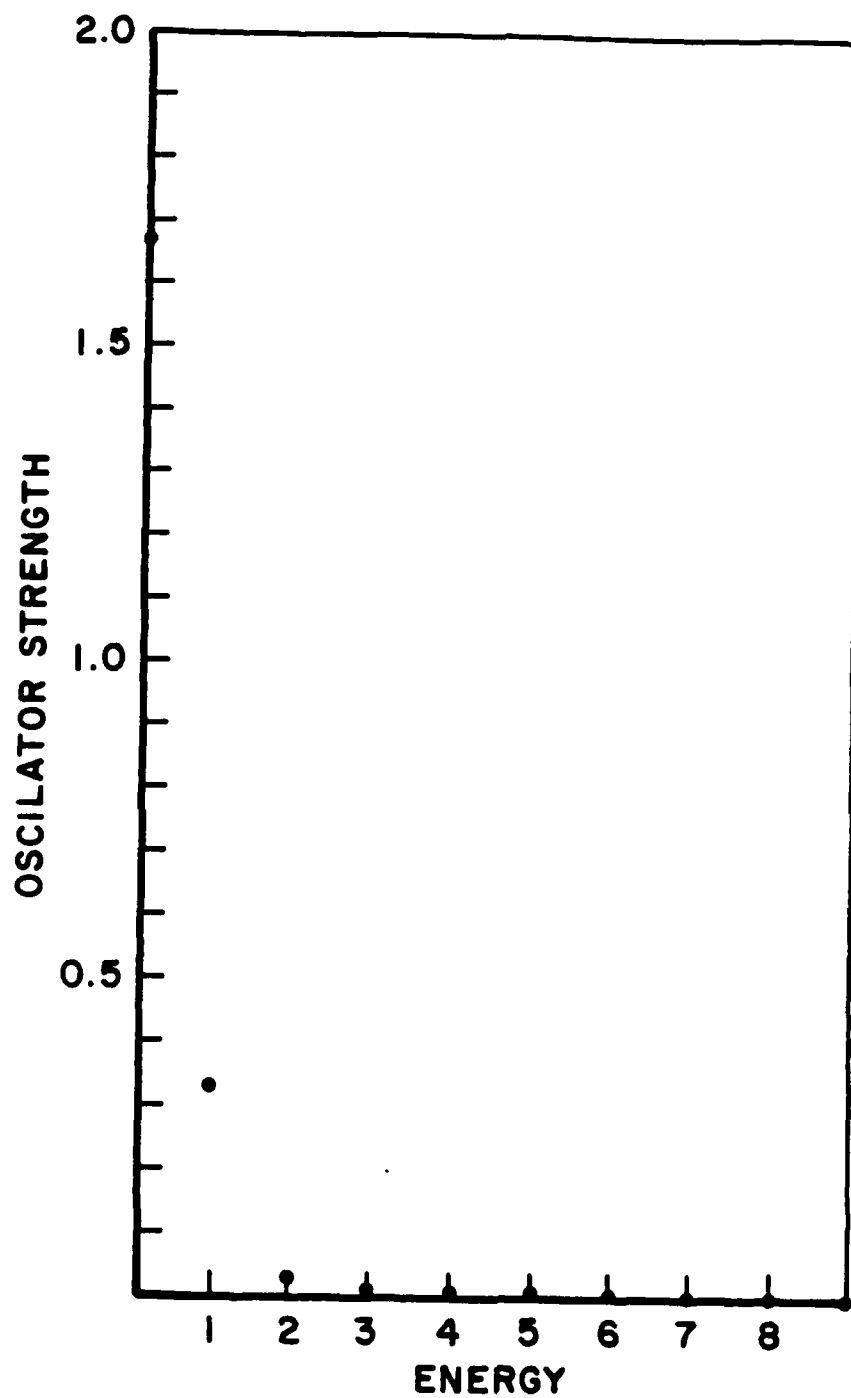


Figure 6. Plot of Oscillator Strength Distribution in the Continuum for the  $2p \rightarrow$  Continuum,  $l=2$  vs. Energy of the Continuum State.

TABLE 6.  
CONTRIBUTIONS TO THE SUM OF THE OSCILLATOR STRENGTHS  
FOR 21p and 31p HELIUM STATES

21p	DISCRETE n≤10	CONTINUUM	TOTAL
nd	0.9248	1.0291* 1.3678**	1.9392* 2.2926**
ns	-0.1531	0.1578* 0.06167**	0.00472* -0.09136**
			1.9439* 2.2012**

31p**	DISCRETE n≤10	CONTINUUM	TOTAL
nd	0.8897	1.1532	2.0429
ns	-0.1468	0.0329	-0.1139
			1.929

\* Calculated using the lower bound technique.

\*\* Calculated using the upper bound technique.

TABLE 7.  
CONTRIBUTIONS TO THE POLARIZABILITY TERMS<sup>†</sup>

j	$\alpha_F$	$\alpha_E$	$\alpha_{F+E} \cdot F^2$
2	0.499	0.739	$1.08 \times 10^{-14}$
3	0.112	0.154	$9.26 \times 10^{-7}$
4	$4.30 \times 10^{-2}$	$5.80 \times 10^{-2}$	$1.49 \times 10^{-5}$
5	$2.11 \times 10^{-2}$	$2.82 \times 10^{-2}$	$1.33 \times 10^{-4}$
6	$1.59 \times 10^{-2}$	$1.59 \times 10^{-2}$	$8.06 \times 10^{-4}$
7	$7.41 \times 10^{-3}$	$9.84 \times 10^{-2}$	$3.62 \times 10^{-3}$
8	$4.93 \times 10^{-3}$	$6.53 \times 10^{-3}$	$1.48 \times 10^{-2}$
9	$3.44 \times 10^{-3}$	$4.55 \times 10^{-3}$	$3.81 \times 10^{-2}$
10	$2.49 \times 10^{-3}$	$3.30 \times 10^{-3}$	0.104
Continuum	0.794	2.1824	$-2.32 \times 10^{-10}$
Total	1.498	3.202	0.161

<sup>†</sup> Atomic units



symmetric gases are theoretically possible. The calculated tensors are applicable to investigations on other physical phenomena.

Tables 8 - 10 contain the fourth-rank scattering tensors for the point groups used in the Raman experiment. Although there are 81 components to these tensors, they have been reduced to a six-by-six matrix form. In this format,  $T_{lm,nr}$  is reduced to  $T_{a,b}$  using the following index reduction

$$\begin{array}{cccccc} 11 & 22 & 33 & 23 & 13 & 12 & . \\ 1 & 2 & 3 & 4 & 5 & 6 \end{array}$$

In this format,  $T_{11,13}$  reduces to  $T_{15}$ ,  $T_{22,26}$  reduces to  $T_{26}$ , and so on. The scattering tensors are not totally symmetric.  $T_{lm,nr}$  is equal to  $T_{ml,nr}$  but not necessarily equal to  $T_{nr,lm}$ .

In view of the discrepancy between theory and experiment, a final experiment was undertaken with liquid benzene. This experiment also yielded a null result, and established that a Raman scattering, and presumably its companion technique, CARS, will not give a useful measurement of electric field strength at fields on the order of 100 kV/cm (10 MV/m).

In summary, the accomplishments of the program were:

- A change in the Rayleigh scattering cross section was observed in a large variety of gases: He, Ne, Ar, Kr,  $N_2$ ,  $CH_4$ ,  $CF_4$ ,  $CCl_2$ ,  $CO_2$ , and  $SF_6$ .
- The change in the Rayleigh signal was studied as a function of the collection angle and the direction of polarization of the incident light.
- Quantitative measurements were made of the field-induced cross sections.

LASER MEASUREMENT OF TRANSIENT HIGH-STRENGTH ELECTRIC FIELDS

FISCAL REPORT

Expenditures were as follows:

Salaries and Wages	\$246,730
Materials and Supplies	34,993
Equipment Rental	4,483
Communications	1,538
Travel	5,608
Equipment	<u>6,474</u>
Total	\$299,827
Budget	298,859
Balance	(968)

TABLE 8.

FIELD-INDUCED SCATTERING TENSORS FOR  
RAMAN ACTIVITY OF THE  $C_s$  AND  $C_{2v}$  POINT GROUPS

 $C_s$ 

$$\begin{bmatrix} a & h & h & 0 & 0 & h \\ h & b & h & 0 & 0 & h \\ h & h & c & 0 & 0 & h \\ 0 & 0 & 0 & e & g & 0 \\ 0 & 0 & 0 & g & f & 0 \\ h & h & h & 0 & 0 & d \end{bmatrix}$$

 $A'$ 

$$\begin{bmatrix} 0 & 0 & 0 & a & e & 0 \\ 0 & 0 & 0 & b & f & 0 \\ 0 & 0 & 0 & c & g & 0 \\ a & b & c & 0 & 0 & d \\ e & f & g & 0 & 0 & h \\ 0 & 0 & 0 & d & h & 0 \end{bmatrix}$$

 $A''$  $C_{2v}$ 

$$\begin{bmatrix} a & d & d & 0 & 0 & 0 \\ d & b & d & 0 & 0 & 0 \\ d & d & c & 0 & 0 & 0 \\ 0 & 0 & 0 & h & 0 & 0 \\ 0 & 0 & 0 & 0 & g & 0 \\ 0 & 0 & 0 & 0 & 0 & f \end{bmatrix}$$

 $A_1$ 

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & a \\ 0 & 0 & 0 & 0 & 0 & a \\ 0 & 0 & 0 & 0 & 0 & a \\ 0 & 0 & 0 & 0 & b & 0 \\ 0 & 0 & 0 & b & 0 & 0 \\ a & a & a & 0 & 0 & 0 \end{bmatrix}$$

 $A_2$ 

$$\begin{bmatrix} 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & 0 & b \\ a & a & a & 0 & 0 & 0 \\ 0 & 0 & 0 & b & 0 & 0 \end{bmatrix}$$

 $B_1$ 

$$\begin{bmatrix} 0 & 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & a & 0 & 0 \\ a & a & a & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & b \\ 0 & 0 & 0 & 0 & b & 0 \end{bmatrix}$$

 $B_2$

TABLE 9.

FIELD-INDUCED SCATTERING TENSORS FOR  
THE  $D_{6h}$  AND  $D_{\infty h}$  POINT GROUPS

$D_{6h}$	$\begin{bmatrix} a & b & d & 0 & 0 & 0 \\ b & a & d & 0 & 0 & 0 \\ d & d & c & 0 & 0 & 0 \\ 0 & 0 & 0 & e & 0 & 0 \\ 0 & 0 & 0 & 0 & e & 0 \\ 0 & 0 & 0 & 0 & 0 & f \end{bmatrix}$	$\begin{bmatrix} b & b & 0 & 0 & 0 & 0 \\ b & b & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & 0 & b \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a \\ a & a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a & 0 & 0 \end{bmatrix}$
	$A_{1g}$	$A_{2g}$	$B_{1g}$
	$\begin{bmatrix} 0 & 0 & 0 & a & a & 0 \\ 0 & 0 & 0 & a & a & 0 \\ 0 & 0 & 0 & b & b & 0 \\ a & c & b & 0 & 0 & 0 \\ c & c & b & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & c & a & 0 \\ 0 & 0 & 0 & c & b & 0 \\ 0 & 0 & 0 & d & d & 0 \\ c & c & d & 0 & 0 & e \\ a & b & d & 0 & 0 & 0 \\ 0 & 0 & 0 & e & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} a & a & d & 0 & 0 & c \\ b & b & d & 0 & 0 & c \\ d & d & 0 & 0 & 0 & d \\ 0 & 0 & 0 & e & 0 & 0 \\ 0 & 0 & 0 & 0 & e & 0 \\ c & c & d & 0 & 0 & f \end{bmatrix}$
$D_{\infty h}$	$B_{2g}$	$E_{1g}$	$E_{2g}$
	$\begin{bmatrix} a & b & d & 0 & 0 & 0 \\ b & a & d & 0 & 0 & 0 \\ d & d & c & 0 & 0 & 0 \\ 0 & 0 & 0 & f & 0 & 0 \\ 0 & 0 & 0 & 0 & e & 0 \\ 0 & 0 & 0 & 0 & 0 & g \end{bmatrix}$	$\begin{bmatrix} d & d & 0 & 0 & 0 & f \\ d & d & 0 & 0 & 0 & f \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & b & c & 0 \\ 0 & 0 & 0 & c & a & 0 \\ f & f & 0 & 0 & 0 & e \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & d & a & 0 \\ 0 & 0 & 0 & d & b & 0 \\ 0 & 0 & 0 & f & c & 0 \\ d & d & f & 0 & 0 & g \\ a & b & c & 0 & 0 & 0 \\ 0 & 0 & 0 & g & 0 & 0 \end{bmatrix}$
	$A_{1g}$	$A_{2g}$	$E_{1g}$
$D_{\infty h}$	$\begin{bmatrix} a & a & b & 0 & 0 & c \\ a & a & b & 0 & 0 & c \\ b & b & 0 & 0 & 0 & d \\ 0 & 0 & 0 & f & 0 & 0 \\ 0 & 0 & 0 & 0 & e & 0 \\ c & c & d & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & d \\ a & a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & d & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} a & a & 0 & 0 & 0 & 0 \\ a & a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & b \end{bmatrix}$
	$E_{2g}$	$E_{3g}$	$E_{4g}$

TABLE 10.

FIELD-INDUCED SCATTERING TENSORS FOR  
THE  $O_h$  AND  $C_{3v}$  POINT GROUPS

$O_h$	$\begin{pmatrix} a & b & c & 0 & 0 & 0 \\ b & d & c & 0 & 0 & 0 \\ c & c & e & 0 & 0 & 0 \\ 0 & 0 & 0 & f & 0 & 0 \\ 0 & 0 & 0 & 0 & f & 0 \\ 0 & 0 & 0 & 0 & 0 & f \end{pmatrix}$	$\begin{pmatrix} a & 0 & a & 0 & 0 & 0 \\ a & 0 & a & 0 & 0 & 0 \\ a & a & 2a & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} f & b & a & 0 & 0 & 0 \\ b & c & a & 0 & 0 & 0 \\ f & e & d & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$
	$A_{1g}$	$A_{2g}$	$E_g$
	$\begin{pmatrix} b & a & 0 \\ a & 0 & 0 \\ 0 & 0 & c \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & b & a \\ 0 & a & c \end{pmatrix}$	$\begin{pmatrix} b & 0 & a \\ 0 & c & 0 \\ a & 0 & 0 \end{pmatrix}$
	$F_{1g}(xy)$	$F_{1g}(yz)$	$F_{1g}(zx)$
	$\begin{pmatrix} c & f & f \\ f & e & b+d \\ f & b+d & e \end{pmatrix}$	$\begin{pmatrix} e & f & b+d \\ f & c & f \\ b+d & f & e \end{pmatrix}$	$\begin{pmatrix} e & b+d & f \\ b+d & e & f \\ f & f & c \end{pmatrix}$
	$F_{2g}(yz)$	$F_{2g}(zx)$	$F_{2g}(xy)$
$C_{3v}$	$\begin{pmatrix} b & c & d & h & 0 & 0 \\ c & b & d & h & 0 & 0 \\ d & d & a & 0 & 0 & 0 \\ h & h & 0 & e & 0 & 0 \\ 0 & 0 & 0 & 0 & e & g \\ 0 & 0 & 0 & 0 & g & f \end{pmatrix}$	$\begin{pmatrix} c & 2c & 0 & b & 0 & 0 \\ 2c & c & 0 & b & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ b & b & 0 & a & 2b & 0 \\ 0 & 0 & 0 & 2b & a & 2b \\ 0 & 0 & 0 & 0 & 2b & 4c \end{pmatrix}$	$\begin{pmatrix} b & b & c & c & c & 2b \\ b & b & c & c & c & 2b \\ c & c & 0 & a & a & 2c \\ c & c & a & 0 & 0 & 0 \\ c & c & a & 0 & 0 & 0 \\ 2b & 2b & 2c & 0 & 0 & 0 \end{pmatrix}$
	$A_1$	$A_2$	$E$

- Computer programs were written to generate confluent hypergeometric wave functions for both discrete and continuum states.
- Oscillator strengths were calculated for discrete-to-discrete and discrete-to-continuum transitions in Helium.
- The contributions to the polarizability of Helium from discrete states were calculated.
- The widely used tables of Bates and Damgaard were extended and calculated more accurately.
- An upper bound on the Stark-induced Raman cross-section of molecules was established.
- Scattering tensors for the quadratic Stark or stress-induced Raman process were calculated for four key point groups.

### 3. TECHNICAL JOURNALS

A manuscript describing the work on Rayleigh scattering and emphasizing the experiment was submitted to Applied Physics Letters. A revised manuscript is in preparation incorporating comments from the reviewers. A companion list of compiled tables will also be submitted for publication by the American Physical Society. A related paper was presented at the AIAA Aerospace Sciences meeting in Reno in January 1987.

#### 4. PROFESSIONAL PERSONNEL

Dr. Roger Becker was the Principal Investigator on the program. Three graduate students obtained their masters' degrees on the program. The titles and the dates of their defenses were:

Blair A. Barbour, "An Experimental Investigation of Stark-Induced Depolarization in Gases of High Azimuthal Symmetry," April 10, 1986.

Alan T. Buswell, "Theory of Stark-Induced Changes in Rayleigh Scattering from Helium," August 1, 1986.

Edward M. Kozak, "A Raman Study on Induced Changes in the Polarizability of Gases and Liquids by a Strong DC Electric Field," June 29, 1988.

In addition, Steven Fairchild conducted experimental work on the program from May until August 1986 and Robert Senn worked on the experimental portion of the program from August to May 1986. All five were or are graduate students in the University of Dayton's Electro-Optics Program.



## 5. INTERACTIONS

The following presentations have been made during the course of the program:

1. Barbour, B. A., "Rayleigh-Scattering Measurements of Electric Field Strength," Poster Session of Applied Spectroscopy (Miami Valley Section), University of Dayton, January 11, 1985.
2. Buswell, A. T., "Quantum Perturbation Theory of Stark-Induced Polarizability," Poster Session of Applied Spectroscopy (Miami Valley Section), University of Dayton, January 11, 1985.
3. Barbour, B. A. and Buswell, A. T., "Stark-Induced Depolarization Rayleigh Scattering," AFIT, AIAA, 11th Annual Minisymposium on Aerospace Science and Technology (won Best Paper award Session XI, Electro-optics and Human Factors), March 19, 1985.
4. Becker, R. J., Barbour, B. A., and Buswell, A. T., "Laser Diagnostics for Electric Field Measurements," 1985 AFOSR/AFRPL Chemical Rocket Research Meeting, Lancaster, CA., March 21, 1985.
5. Barbour, B. A. and Becker, R. J., "Measurement of Applied Electric-Field Strengths," Ohio Sectional Meeting of the American Physical Society, University of Cincinnati, April 13, 1985.
6. Buswell, A. T. and Becker, R. J., "Calculations of Stark-Induced Depolarization," Ohio Sectional Meeting of the American Physical Society, University of Cincinnati, April 13, 1985.

7. Buswell, A. T., "Theoretical Estimates of Stark-Induced Polarizability," Ohio Sectional Meeting of the American Physical Society, Case Western Reserve University, October 12, 1985.
8. Buswell, A. T., "Theoretical Calculations of Stark-Induced Polarizabilities," Poster Session of Applied Spectroscopy (Miami Valley Section), The Ohio State University, Columbus, OH, January 10, 1986.
9. Buswell, A. T. and Barbour, B. A., "Laser Measurement of Electric Field Strength - Theory and Experiment," Graduate student paper session of the Society for Applied Spectroscopy, University of Cincinnati, February 8, 1986.
10. Buswell, A. T., "Theoretical Estimates of Optical Polarizability in a DC Electric Field," AFIT, AIAA, 12th Annual Minisymposium on Aerospace Science and Technology, March 24, 1986.
11. Barbour, B. A., "Rayleigh Scattering Experiments on Electric Field Strength in Gases," AFIT, AIAA, 12th Annual Minisymposium on Aerospace Science and Technology, March 24, 1986.
12. Buswell, A. T. and Barbour, B. A., "Measurements of Electric Field Strength Using Rayleigh Scattering," Ohio Sectional Meeting of the American Physical Society, April 11-12, 1986.
13. Becker, R. J., Barbour, B. A., and Buswell, A. T., "Laser Diagnostics for Electric Field Measurements," 1986 AFOSR/AFRPL Rocket Research Meeting, Lancaster, CA, September 11, 1986.

14. R. J. Becker, "Rayleigh Probe for Nonintrusive Electric-Field Measurements," OS/APS Fall Meeting, Cleveland, OH, October 11, 1986.
15. Becker, R. J., Buswell, A. T., and Barbour, B. A., "Rayleigh Scattering as a Non-intrusive Diagnostic for Electric Field Strength," OSA Annual Meeting, Seattle, WA, October 22, 1986.
16. R. A. Senn and R. J. Becker, "Optical Measurements of Electric-Field Strength," Cincinnati SAS Student Meeting, Miamisburg, OH, February, 1987.
17. R. A. Senn and R. J. Becker, "Optical Measurements of Electric Field Strength in Gases," AIAA Minisymposium, Wright-Patterson Air Force Base, OH, March 1987.
18. R. J. Becker, "Laser Measurements of Transient, High-Strength Electric Fields," University Park, PA, June 24, 1987.
19. Edward M. Kozak, Jr., David Grote, and Robert Cobb, "Theoretical Estimates of Optical Polarizability in a DC Electric Field," Society for Applied Spectroscopy Poster Session, Dayton, Ohio, January 16, 1987.
20. Edward M. Kozak, Jr., "Optical Measurements of Electric Field Strengths in Gases," 1987 Fall Meeting of the American Physical Society, Youngstown, Ohio October 10, 1987.
21. Edward M. Kozak, Jr., "Optical Measurements of Electric Field Strengths in Gases and Liquids," Society for Applied Spectroscopy Poster Session, Ohio State University, Columbus, Ohio, January 15, 1988.

22. Edward M. Kozak, Jr., "Optical Measurements of Electric Field Strengths in Gases," American Institute of Aeronautics and Astronautics 14th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 31, 1988.
23. Edward M. Kozak, Jr., "An Analysis of a Possible Probe Technique to Study the Local Electric Field Strengths of Gases," 1988 Joint Spring Meeting of the Ohio Section of the American Association of Physics Teachers, Ohio State University, Columbus, Ohio, April 15-16, 1988.

Communication has also been maintained with Dr. Wan Roh of AFIT and Drs. Bish Ganguly and Alan Garsgadden of the Plasma Physics group at AFWAL.

## 6. PATENTS

A patent disclosure has been filed on the Rayleigh scattering method, entitled "Rayleigh Scattering Measurement of Electric Field Strengths."

## 7. ADDITIONAL CONSIDERATIONS

The mission of this program has been to make scientific advances leading to a determination of the feasibility of performing optical measurements of electric field strengths in plasmas. The experimental work has established that Rayleigh scattering is not suitable for this purpose in gases, except possibly at very high pressures, as may occur in some high-power switches. Rayleigh scattering and related elastic scattering processes may be useful in liquids, glasses, and crystalline solids. It would be straightforward to continue the Rayleigh work in condensed matter. If such experiments were undertaken, a full inquiry into the sources of the various noise contributions in the experiment could be made, and a full experimental investigation of the nature of the Stark effect on elastic scattering processes would be completed. The work reported here has laid the groundwork for such an experiment.

The theoretical work undertaken in the program is of great value and should be pursued. These calculations can be extended to most of the atoms in the periodic table in a straightforward manner. This would provide valuable information on selection rule breakdown in emission, absorption, fluorescence, and resonance experiments as well as in Rayleigh scattering. The necessary work for accomplishing most of the needed calculations has already been done; extensions of the calculations involving discrete states to other atoms can proceed on the basis of work already accomplished. The helium calculation can also be extended to other atoms.